P4 Effect of Swirl and Momentum Distribution on Thermal Non-uniformities and Emissions in Premixed Flames

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Abstract

Premixed natural gas combustors are attractive for utility applications due to the their low NO_x potential as well as low emission levels of CO, UHC and soot. The lean premixed combustion reduces peak flame temperature in combustors as compared to the near stoichiometric flame temperatures obtained near the fuel-air interface in diffusion flames. The degree of premixing controls the thermal field uniformity of premixed flames and the corresponding emission levels. The Extent of thermal nonuniformity in premixed combustors depends on the input and operational parameters of the combustor including premixing method, turbulence level, degree and distribution of swirl in the combustor. The non-uniformity in thermal field can have an influence on the overall performance of the combustor, including stability limits and emissions. The goal of our program are to examine (a) thermal field non-uniformities in premixed/partially premixed flames, (b) role of swirl and momentum distribution in a premixed burner on thermal field non-uniformity, (c) thermal time scales and their correlation with the emission levels, and (d) optimum levels of swirl and momentum distribution in a premixed burner for uniform thermal field and low emission levels. Results obtained to-date have shown that premixed swirl combustors can possess large integral time scales of temperatures under certain condition. In general these large time scales are correlated with the emission of trace pollutants including NO_x

During the reported period experimental date were taken to obtain structural information on several flames obtained using the double concentric swirl burner. Information on the

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distribution of OH radical species as well as CH and C_2 have also been obtained from a flame. Detailed insight on the distribution of radical species in premixed and partially premixed flames assist in understanding the unmixedness and flame structure.

In addition, further analysis has also been carried out on the flame thermal signatures and their correlation with the overall emission levels. Several premixed and partially premixed flames were further investigated to determine mean and fluctuating temperatures, power spectral density, probability density and temperature auto-correlation in order to provide comprehensive understanding of the temperature distribution and the degree of thermal signature variation in these flames. Temperature auto-correlation data provide information on the integral-time scale and micro-time scale of temperatures in flames. Emission data on NO_x , HC, and CO have been obtained at different swirl and momentum distributions to the incoming mixture. The emissions data combined with the corresponding thermal signature data provides an insight on the role of input swirl distribution on the combustion and emission characteristics. The results from the premixed and partially premixed flames are compared in order to determine the role of swirl and flow momentum distribution effects on flow structures and flame characteristics.

The results obtained show that the distribution of swirl in the burner has a strong influence on the flame thermal signatures. Distribution of swirl and flow momentum distribution to the burner affects the thermal field and emission levels. In general large values of the integral time scale of temperatures result in higher levels of NO_x , CO and UHC. Micro-thermal time scales in the combustor assist in good mixing of the reactants to the micro-scale level.

The conventional definition of mixedness is a dimensionless parameter that is a function of a specific scalar field. The analytical expressions for swirling flows are incorporated into the expression on mixedness in premixed flames. These expressions are then used to simulate the thermal nonuniformities in premixed swirling flames. The simulations are then used to compare with the results obtained experimentally.

We have continued to provide industrial collaborations with Allison, Pratt & Whitney, Solar and GE. These collaborations have proven to be very beneficial to each party in addition to the fruitful exchange of ideas and direct benefits of our results to industry.

Acknowledgments

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Influence of Swirl on Thermal Mixedness in Premixed and Partially Premixed Combustion Systems

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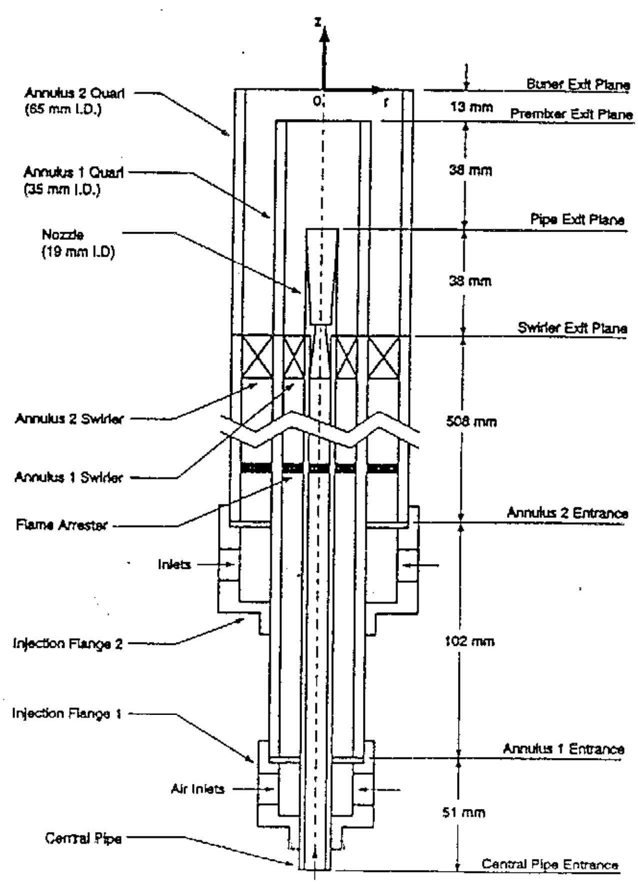
Motivation

- Mixers used in premixed and partially premixed combustors do not provide uniform and homogeneous reactant mixture at the microscale level
- Non-uniformities in the gas flow have a significant effect on combustion and emission
- Swirlers used for flame stabilization provide significant influence on combustion and emission

Objectives

- Determine the effects of swirl and axial momentum distribution on the structure of premixed and partially premixed flames
- Investigate the effects of radial distribution of equivalence ratio on combustion characteristics
- Provide guidelines on advanced mixing configurations for archieving high efficiency and low pollution combustion

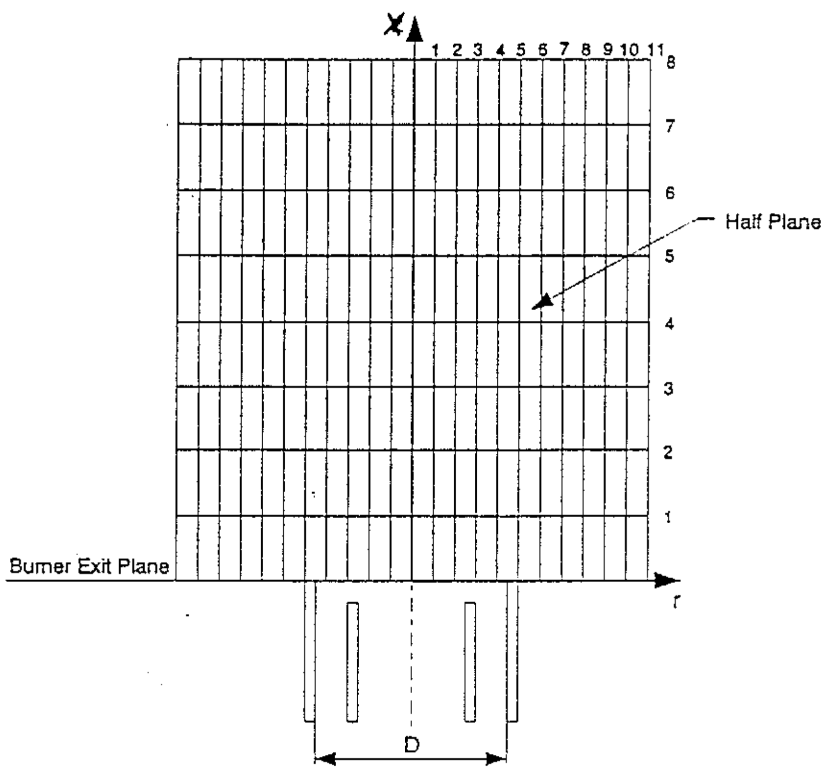
Schematic of the Premixed Burner



Experiments

- Test matrix for all examined flames
- Direct flame photographs
- OH concentration distribution
- Mean and fluctuating temperature data, power spectra, and thermal time scales

Temperature Measurements



108 Sampling Probing Locations in the Flames

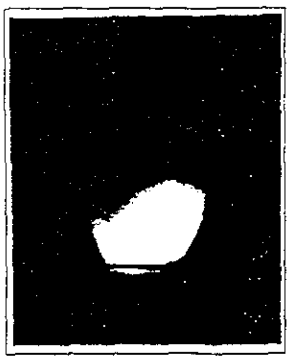
Test Matrix

Flame	1	3	5
Swirl Number	0.4	0.4	0.4
Mom. Ratio	0.3	0.7	1.1
Eq. Ratio CP	0.625	0.625	0.625
Eq. Ratio AN1	0.625	0.625	0.625
Eq. Ratio AN2	0.625	0.625	0.625

Flame	11	13	15
Swirl Number	0.4	0.4	0.4
Mom. Ratio	0.3	0.7	1.1
Eq. Ratio CP	0.7	0.7	0.7
Eq. Ratio AN1	0.6	0.6	0.6
Eq. Ratio AN2	0.391	0.3	0.231

Flame	2	4	6
Swirl Number	0.7	0.7	0.7
Mom. Ratio	0.3	0.7	1.1
Eq. Ratio CP	0.625	0.625	0.625
Eq. Ratio AN1	0.625	0.625	0.625
Eq. Ratio AN2	0.625	0.625	0.625

Flame	12	14	16
Swirl Number	0.7	0.7	0.7
Mom. Ratio	0.3	0.7	1.1
Eq. Ratio CP	0.7	0.7	0.7
Eq. Ratio AN1	0.6	0.6	0.6
Eq. Ratio AN2	0.391	0.3	0.231

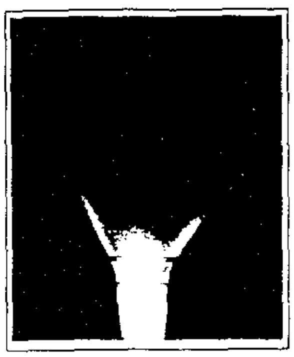


Flame 11: $S = 0.4$; $M \approx 0.3$;
$\phi_{total} = 0.462$; $\phi_{cp} = 0.7$;
$\phi_{an1} = 0.6$; $\phi_{an2} = 0.391$

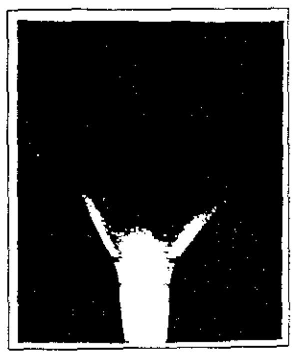
Flame 13: $S = 0.4$; $M \approx 0.7$;
$\phi_{total} = 0.418$; $\phi_{cp} = 0.7$;
$\phi_{an1} = 0.6$; $\phi_{an2} = 0.3$

Flame 15: $S = 0.4$; $M \approx 1.1$;
$\phi_{total} = 0.390$; $\phi_{cp} = 0.7$;
$\phi_{an1} = 0.6$; $\phi_{an2} = 0.231$

Flame 12: $S = 0.7$; $M \approx 0.3$;
$\phi_{total} = 0.462$; $\phi_{cp} = 0.7$;
$\phi_{an1} = 0.6$; $\phi_{an2} = 0.391$



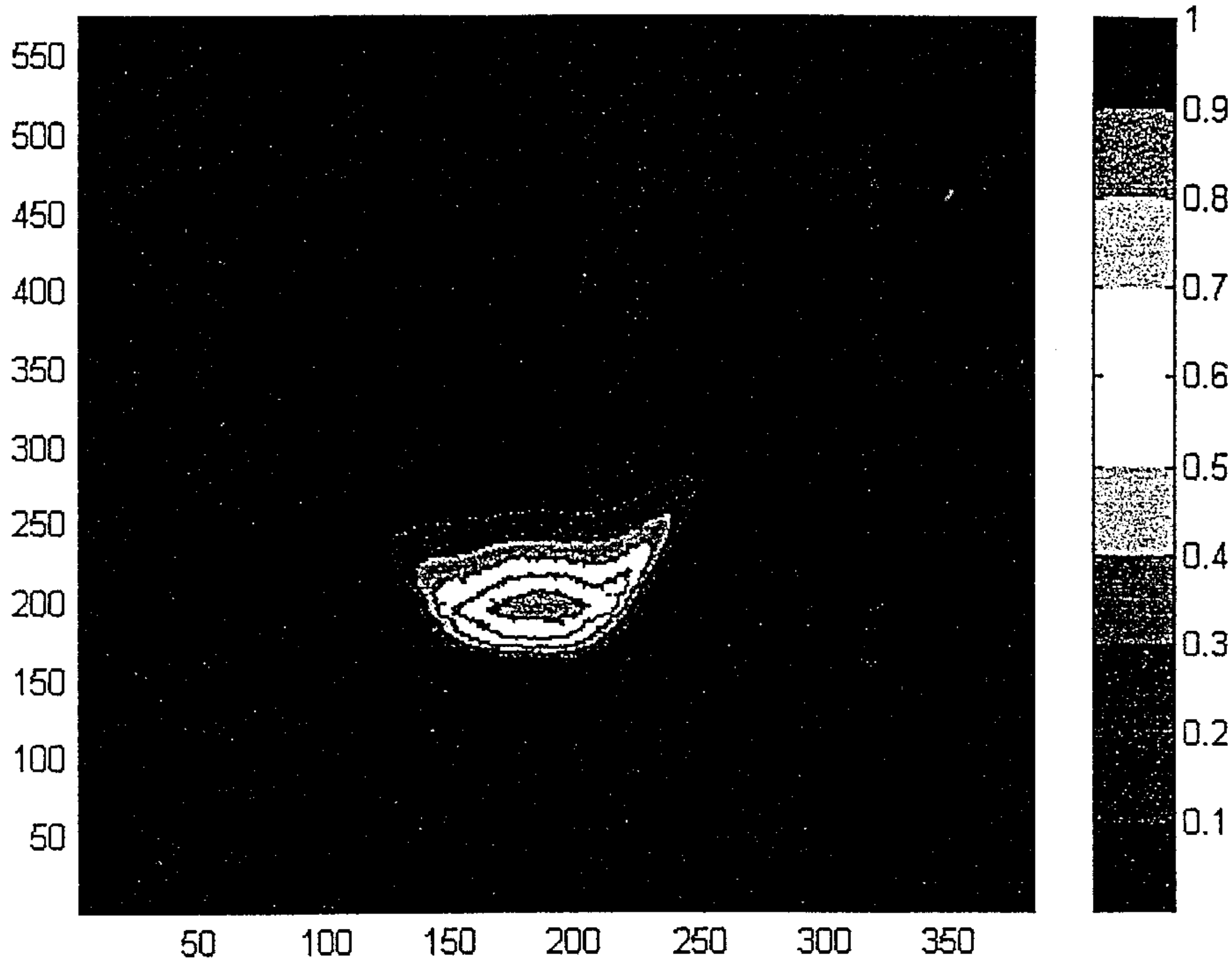
Flame 14: $S = 0.7$; $M \approx 0.7$;
$\phi_{total} = 0.418$; $\phi_{cp} = 0.7$;
$\phi_{an1} = 0.6$; $\phi_{an2} = 0.3$



Flame 16: $S = 0.7$; $M \approx 1.1$;
$\phi_{total} = 0.390$; $\phi_{cp} = 0.7$;
$\phi_{an1} = 0.6$; $\phi_{an2} = 0.231$

Photographs of Partially Premixed Flames

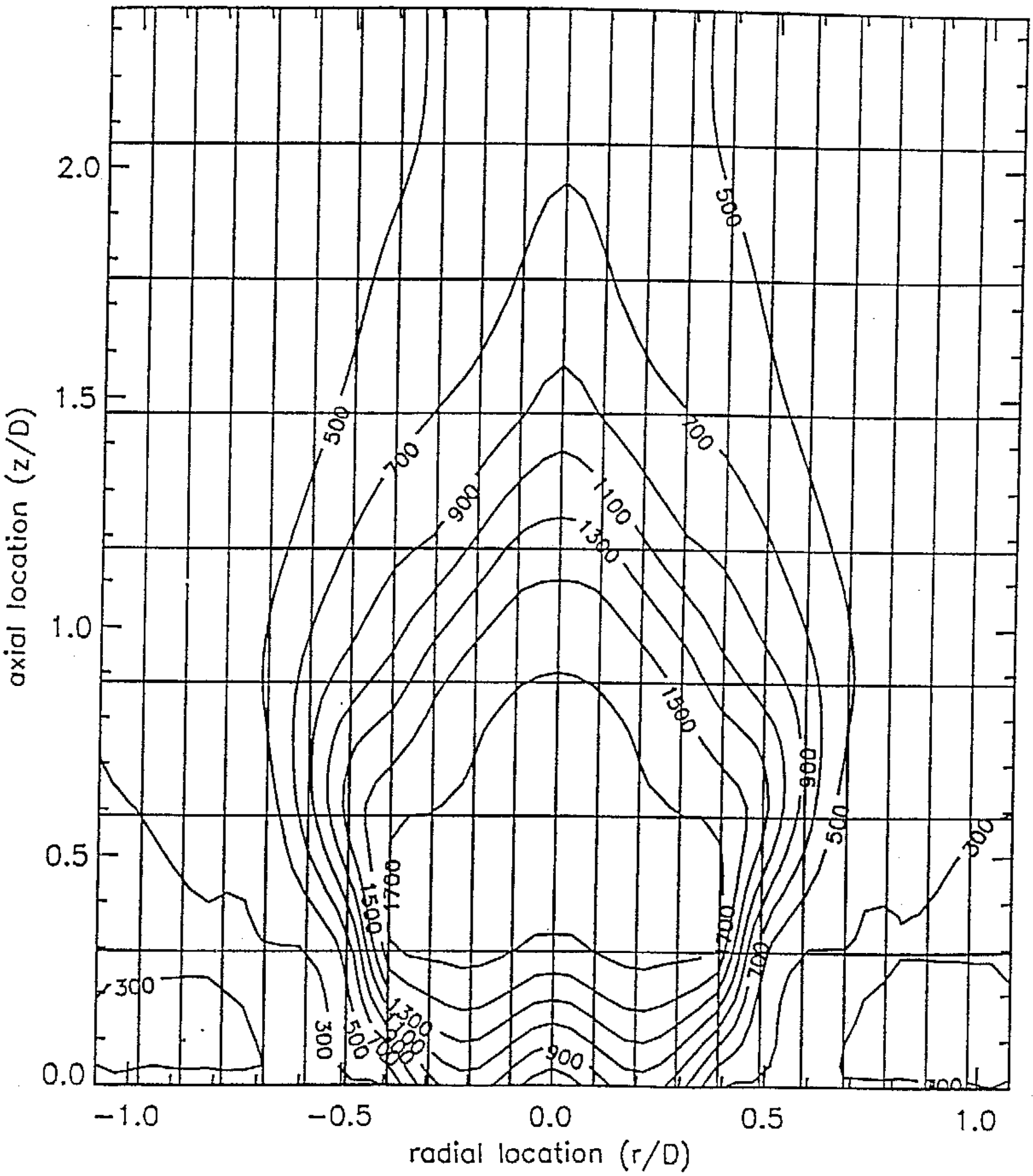
OH Concentration Profile of Flame 1



Case 11

S=0.4; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

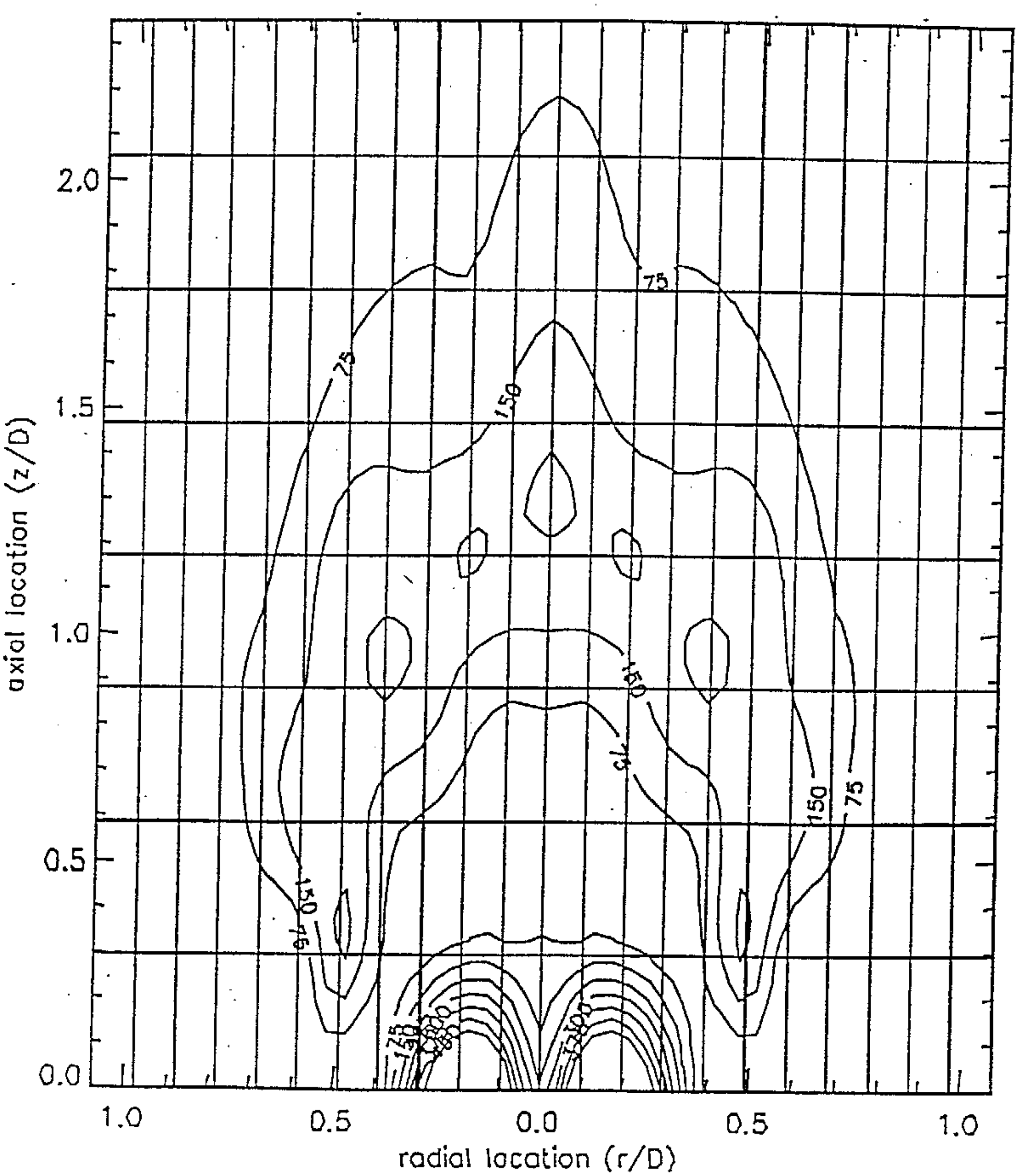


Mean Temperature Contour

Case 11

S=0.4; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391



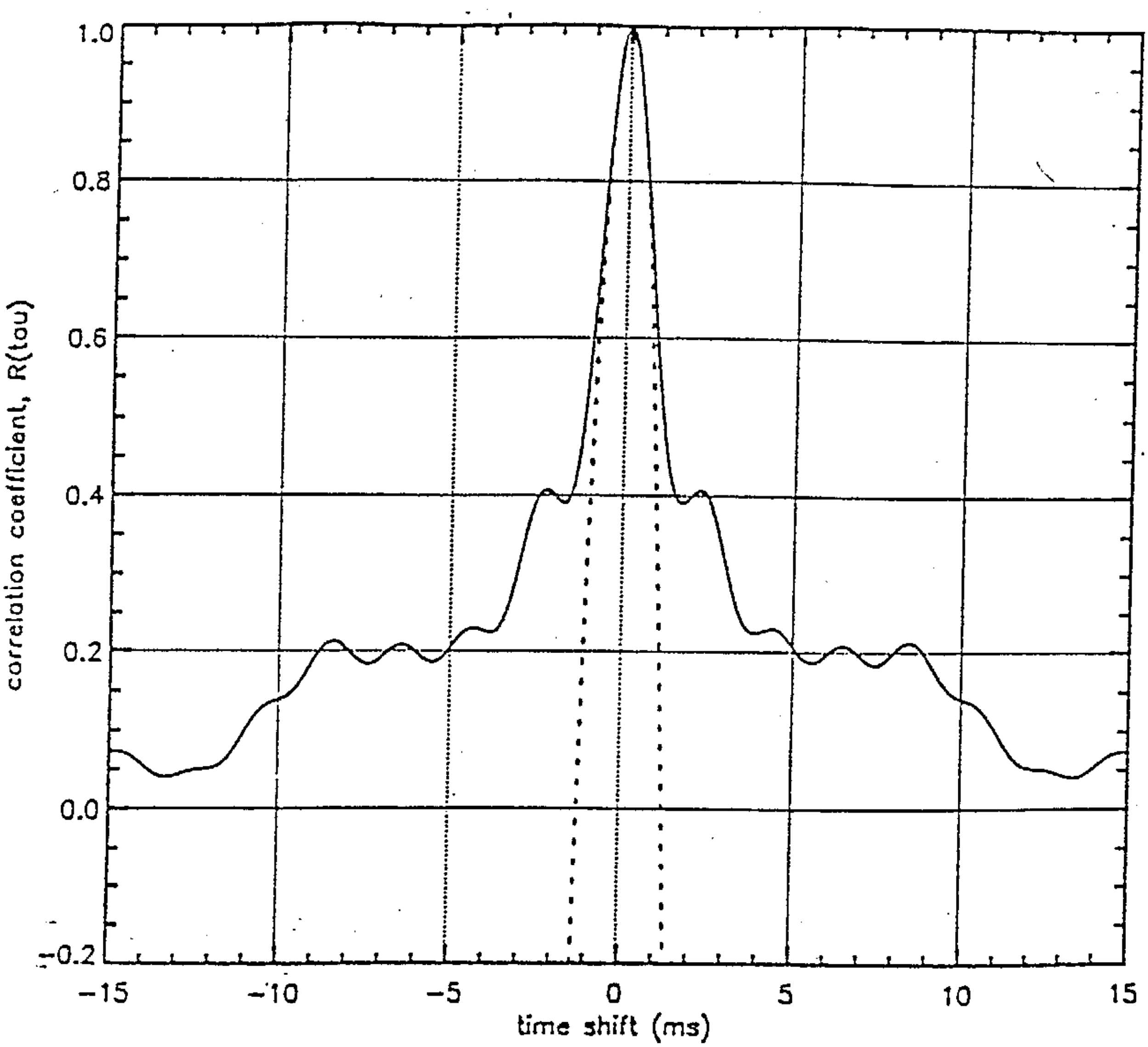
Fluctuating Temperature Contour

Case 11

S=0.4; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.00; x/D=0.59



Correlation Coefficient

Integral scale=6.84 ms

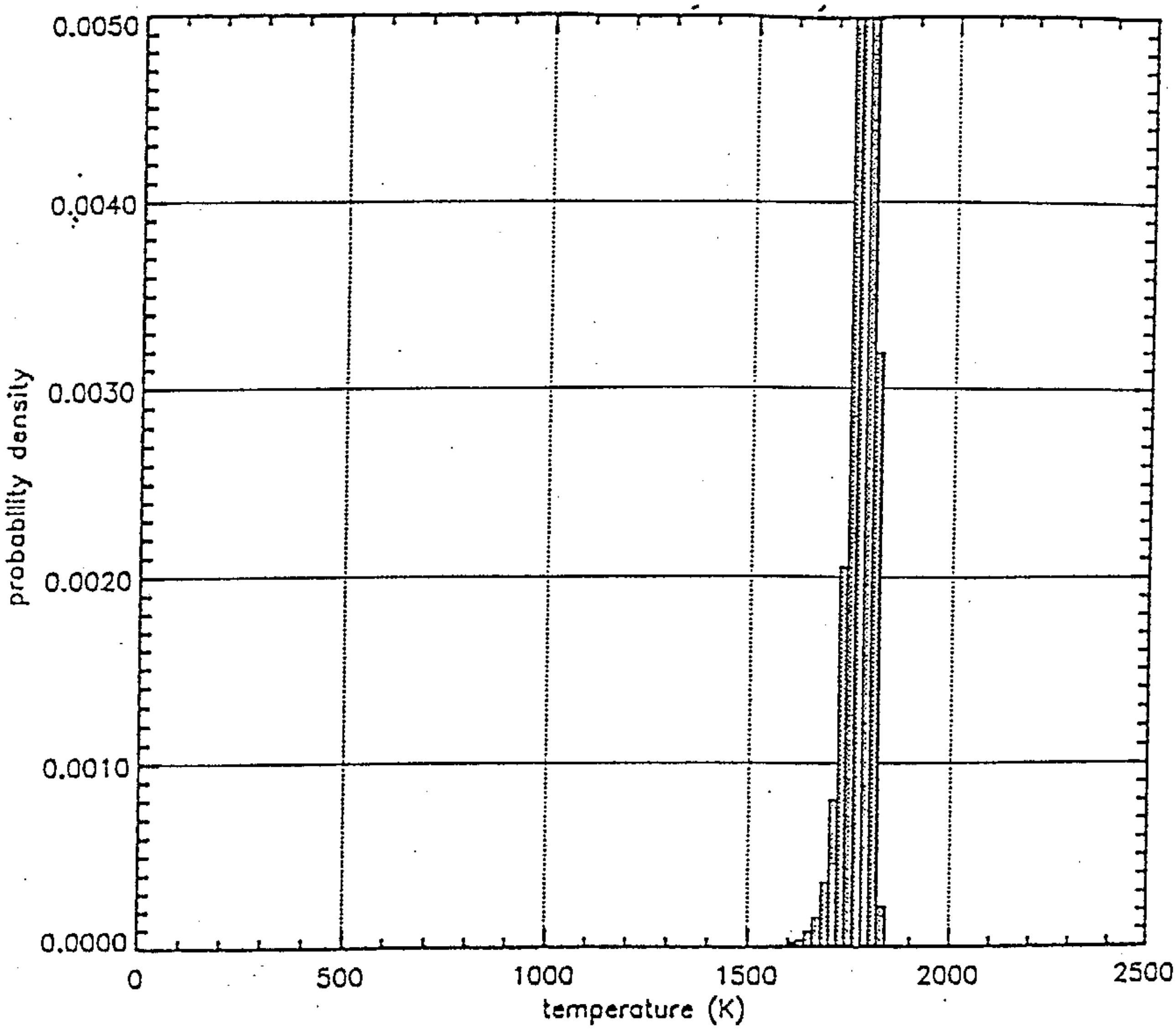
Micro-scale=1.24 ms

Case 11

S=0.4; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.00; x/D=0.59



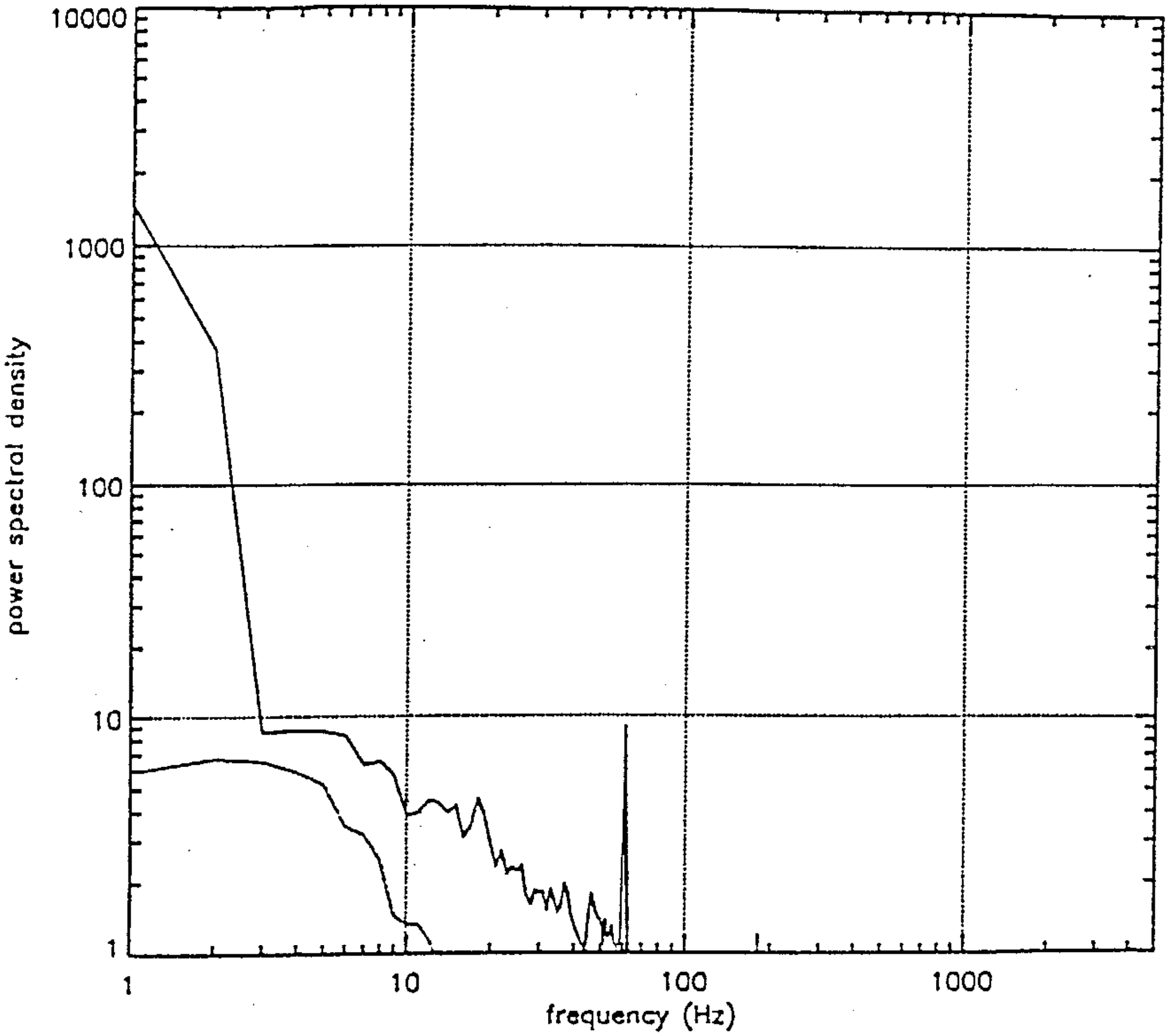
Probability Density Function

Case 11

S=0.4; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.00; x/D=0.59



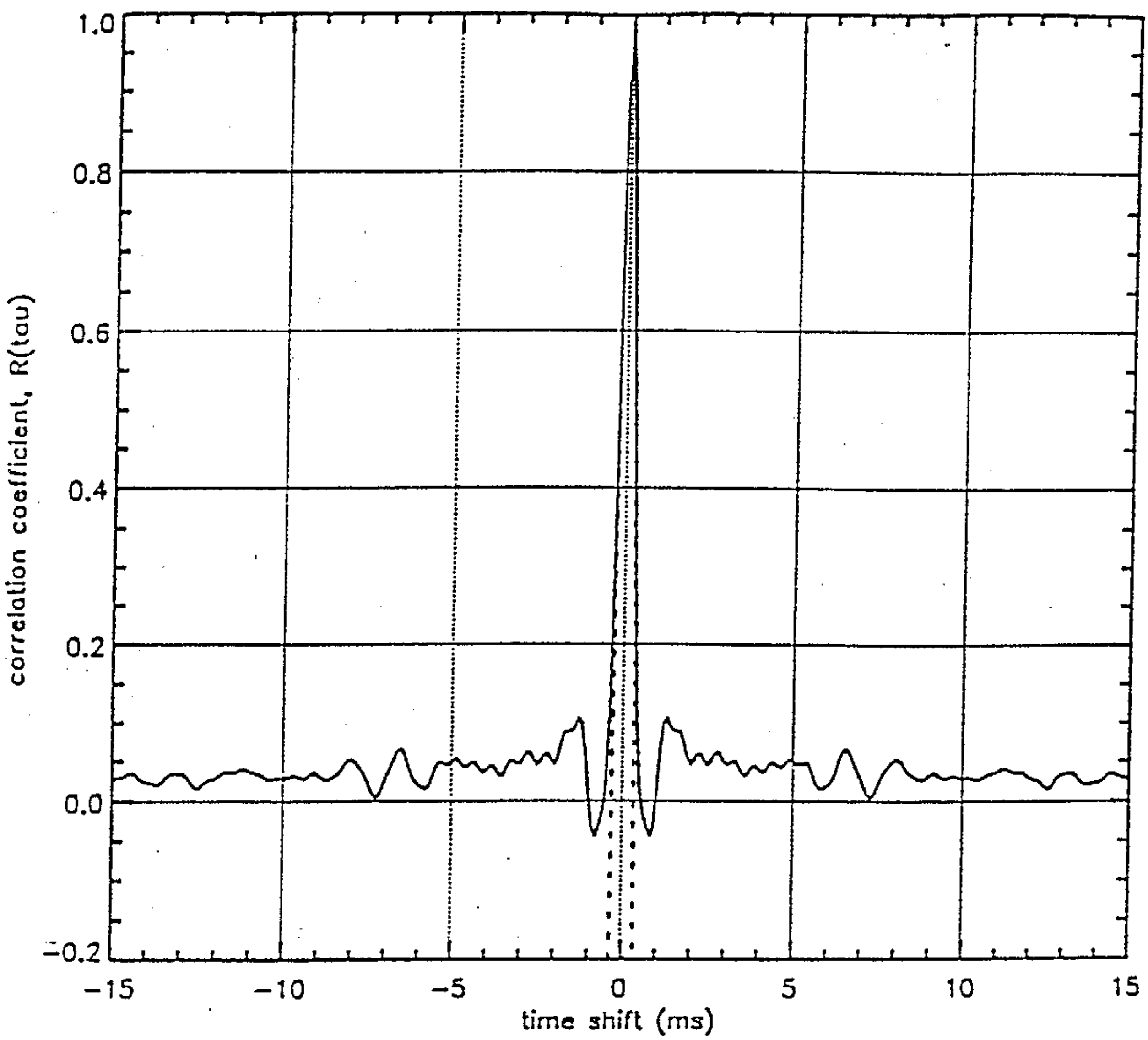
Power spectral Density

Case 11

$S=0.4$; $M \approx 0.3$; $\phi_{total}=0.462$;

$\phi_{cp}=0.7$; $\phi_{an1}=0.6$; $\phi_{an2}=0.391$

Location: $r/D=0.59$; $x/D=0.59$



Correlation Coefficient

Integral scale=1.53 ms

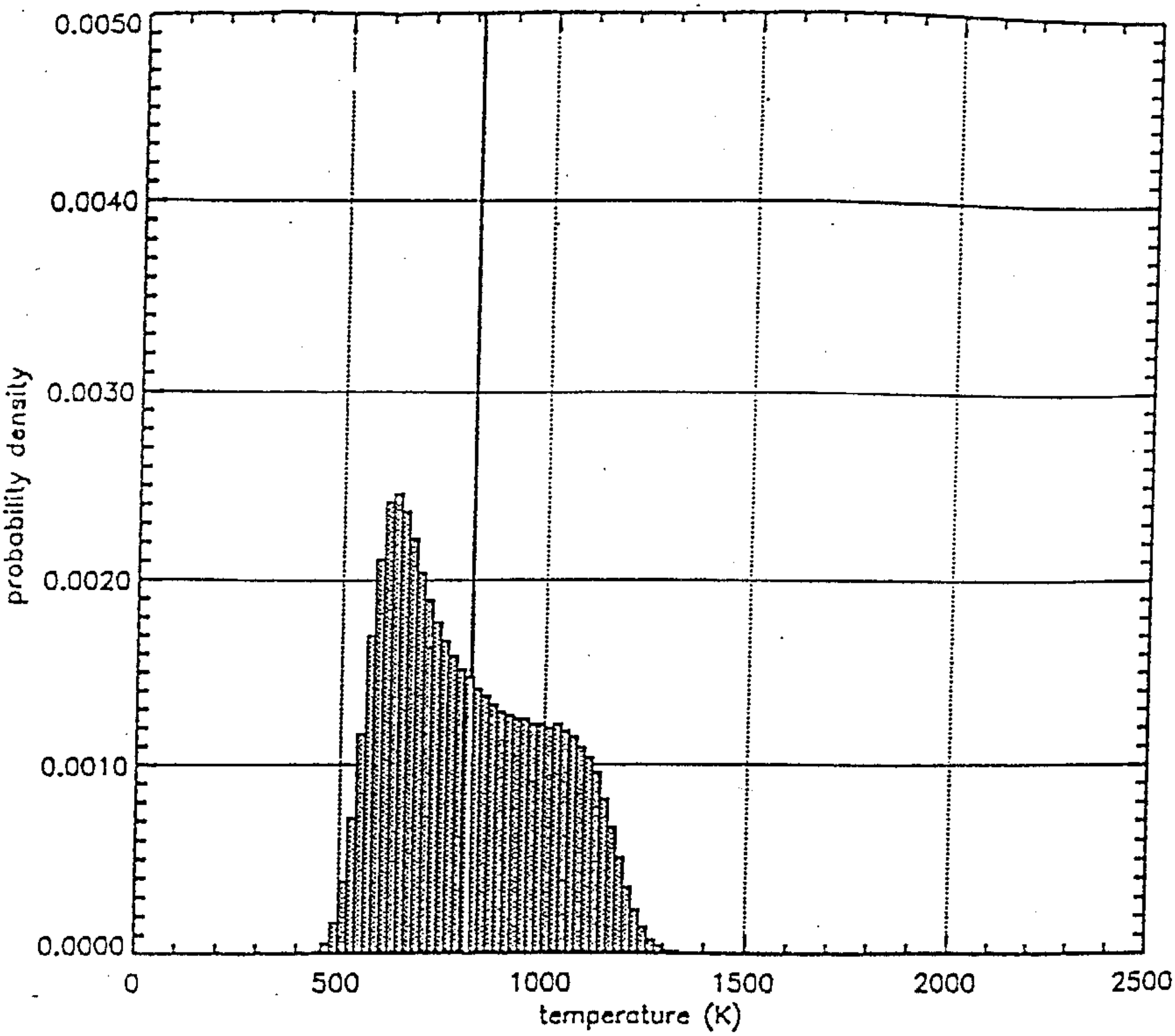
Micro-scale=0.32 ms

Case 11

S=0.4; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.59; x/D=0.59



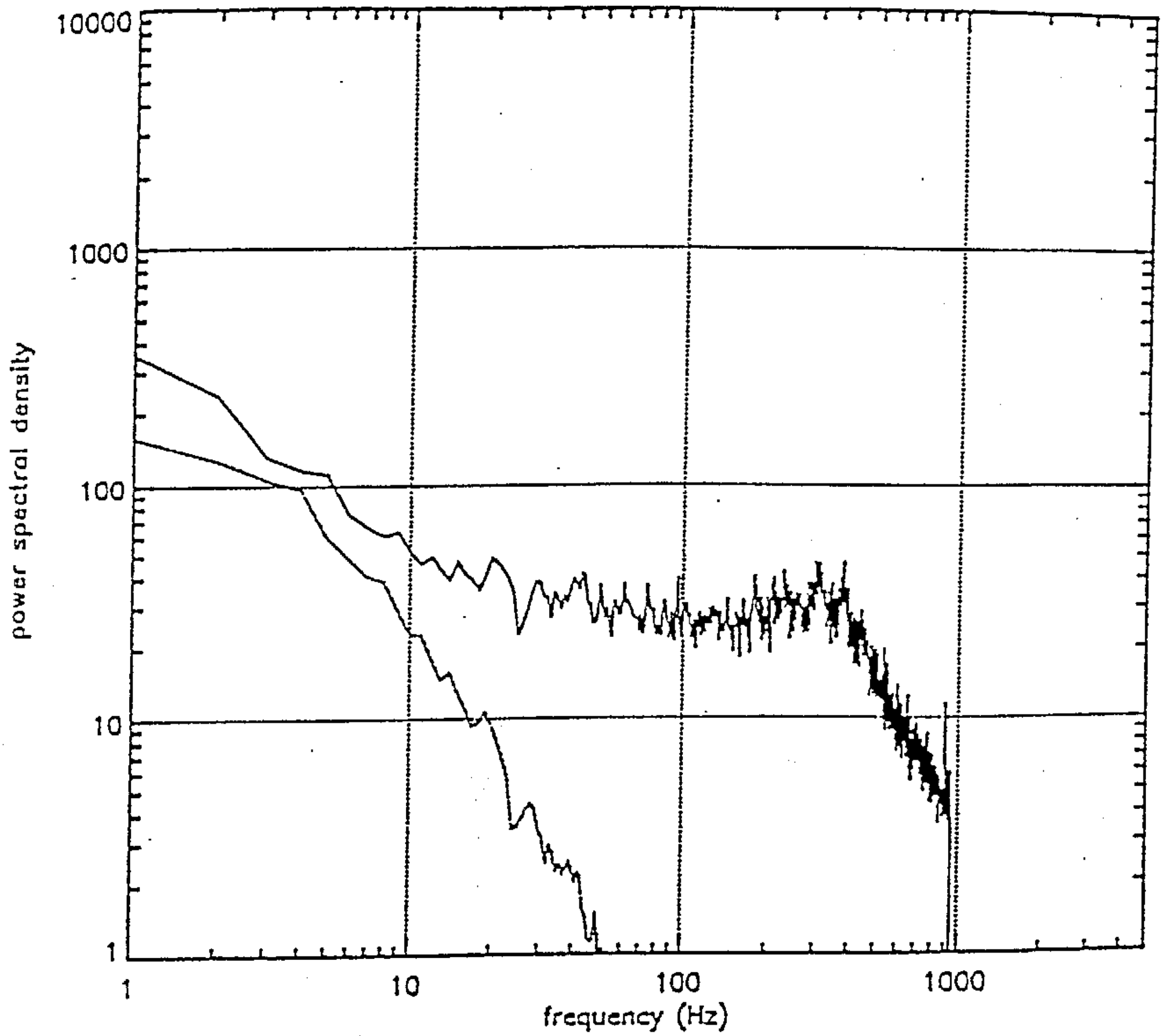
Probability Density Function

Case 11

S=0.4; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.59; x/D=0.59



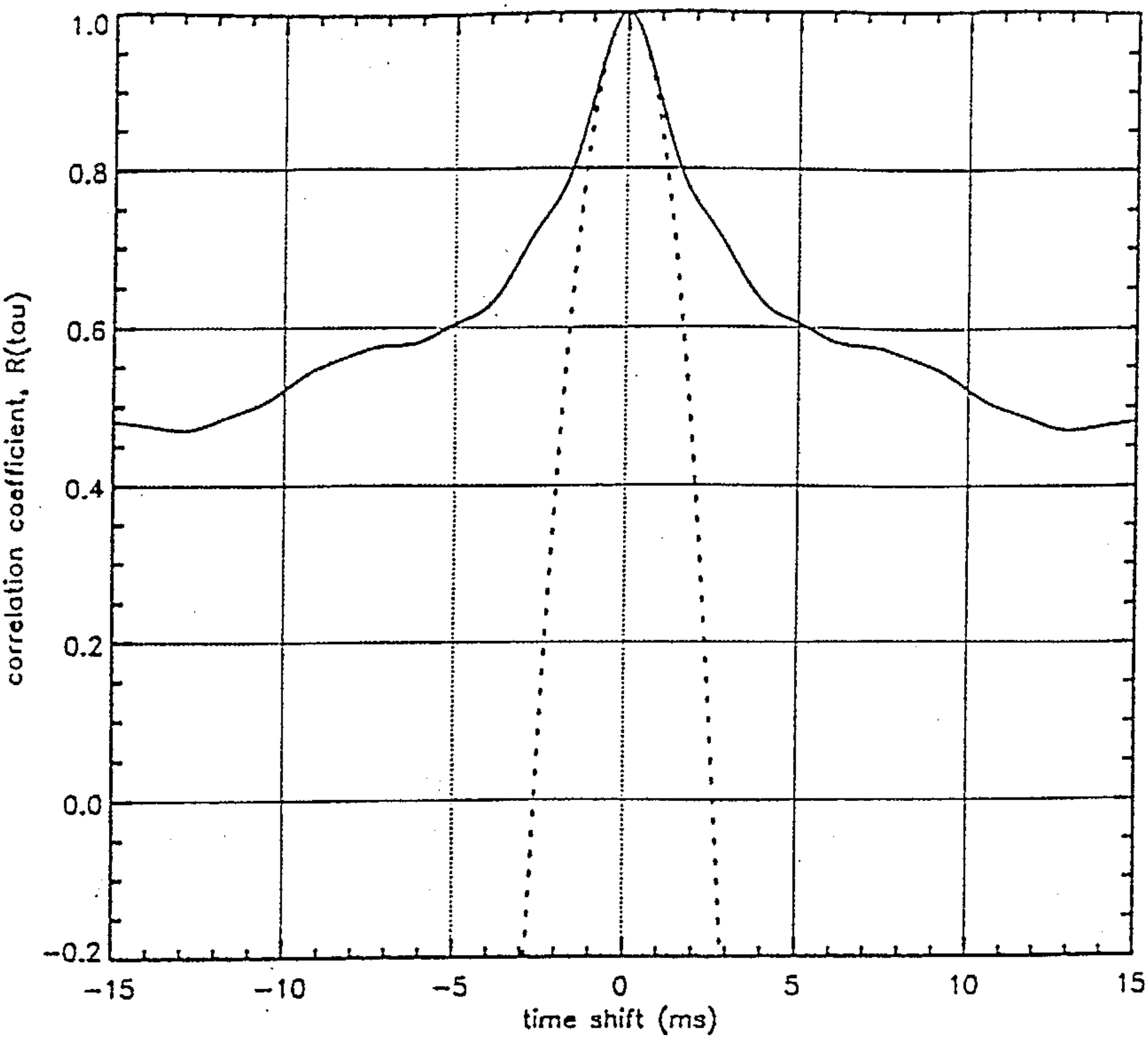
Power Spectral Density

Case 11

S=0.4; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.00;x/D=2.05



Correlation coefficient

Integral scale=18.07 ms

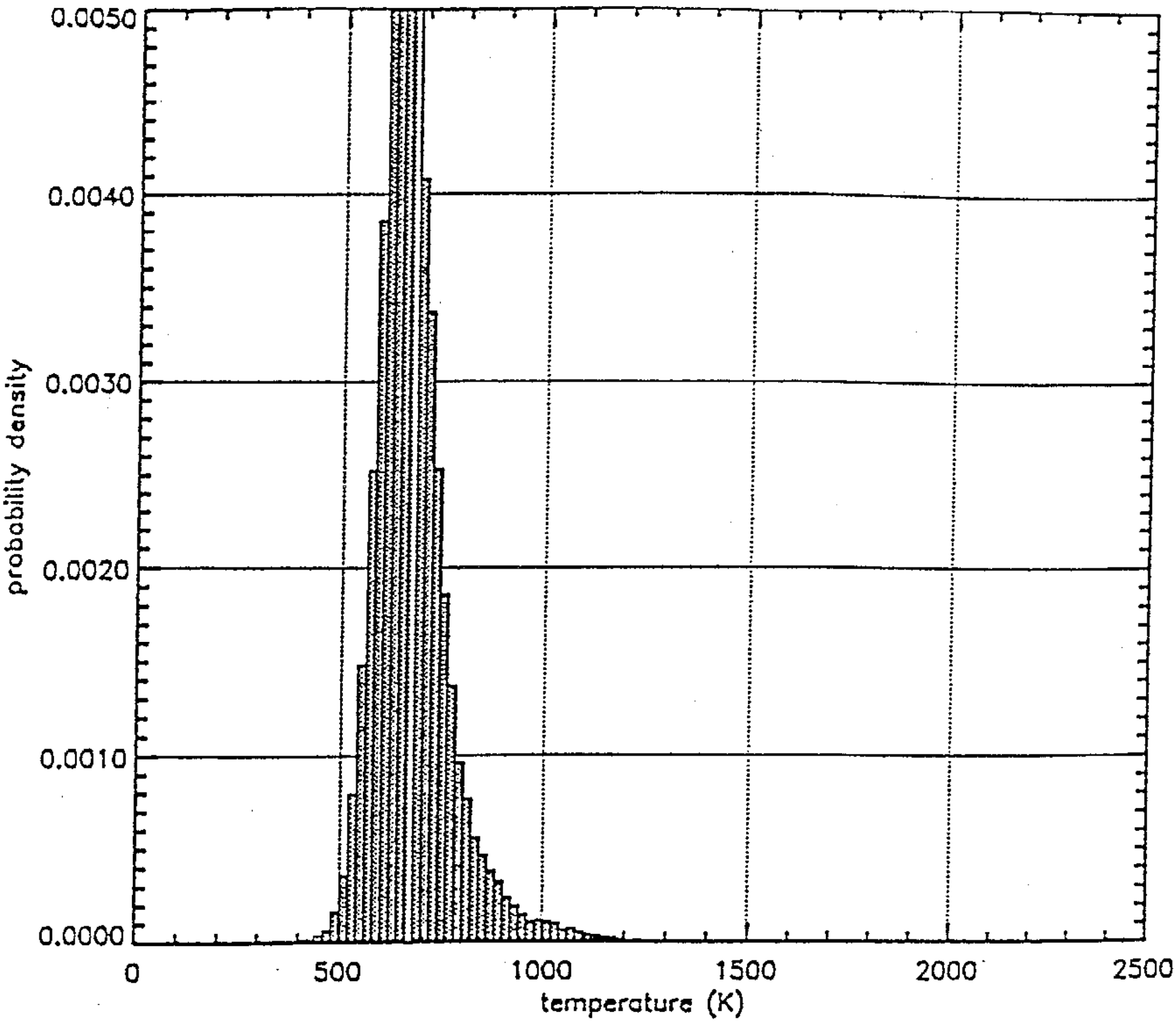
Micro-scale=2.62 ms

Case 11

S=0.4; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.00; x/D=2.05



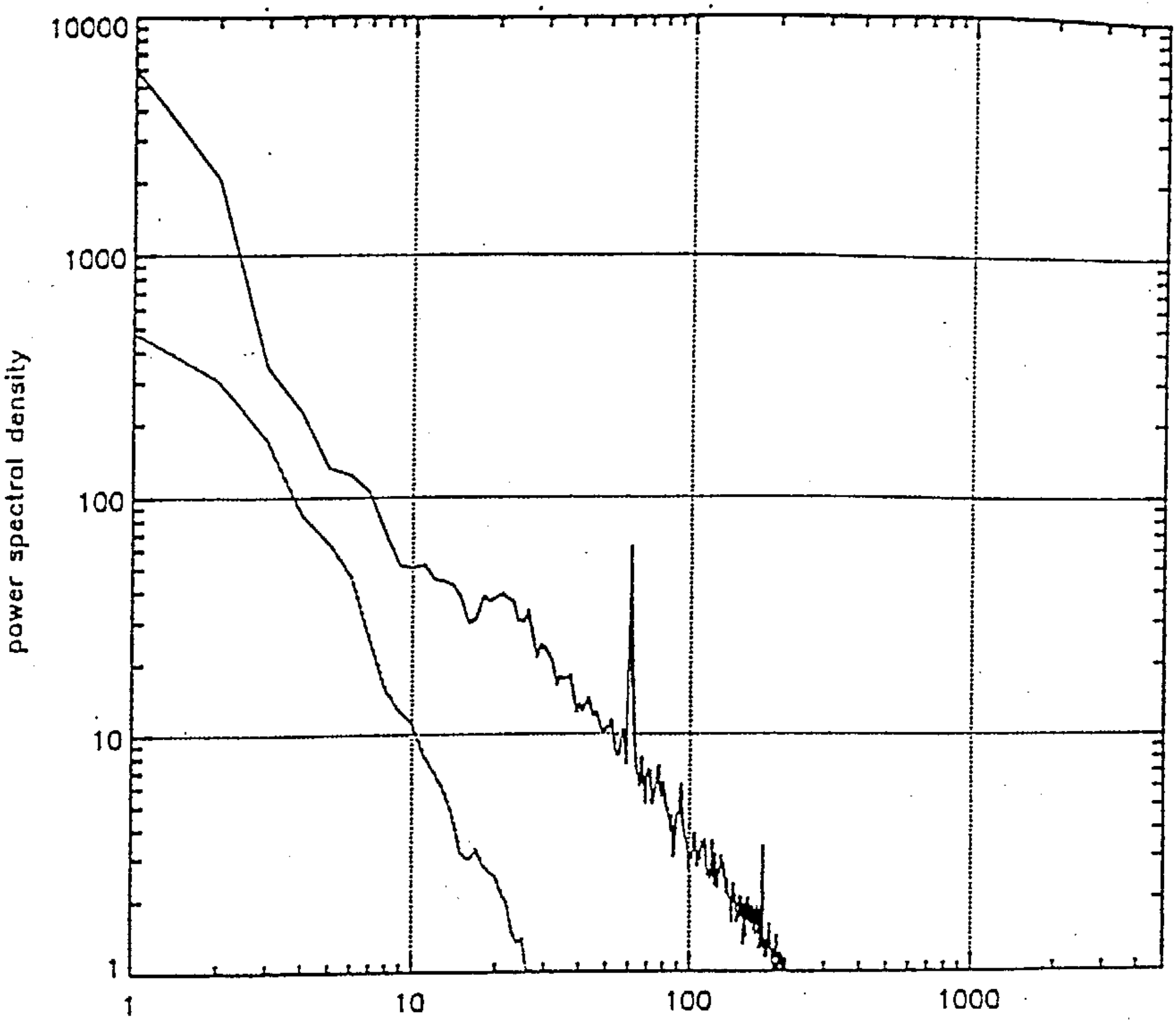
Probability Density Function

Case 11

S=0.4; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.00; $\cancel{x}$/D=2.05

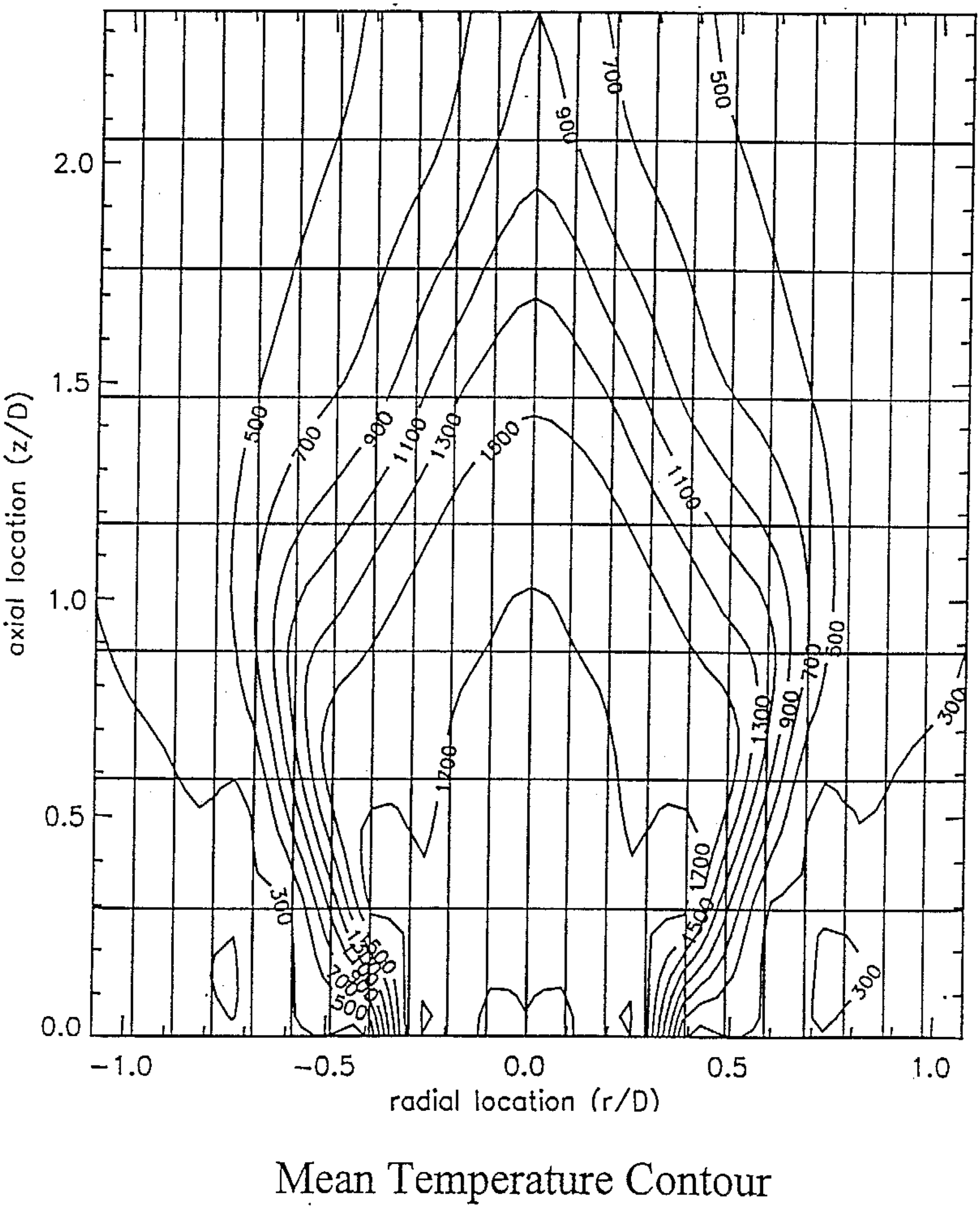


Power Spectral Density

Case 12

S=0.7; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

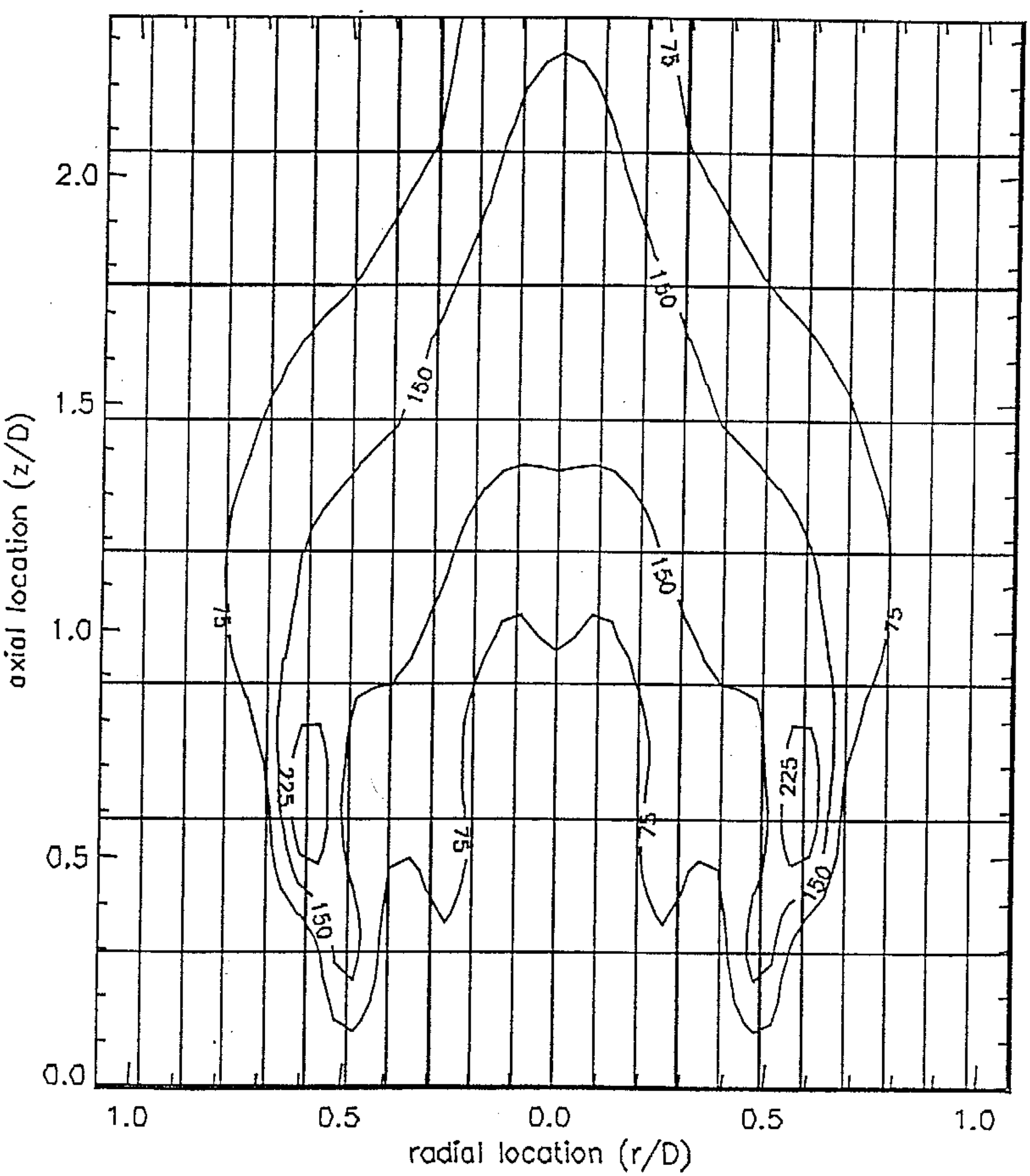


Mean Temperature Contour

Case 12

S=0.7; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391



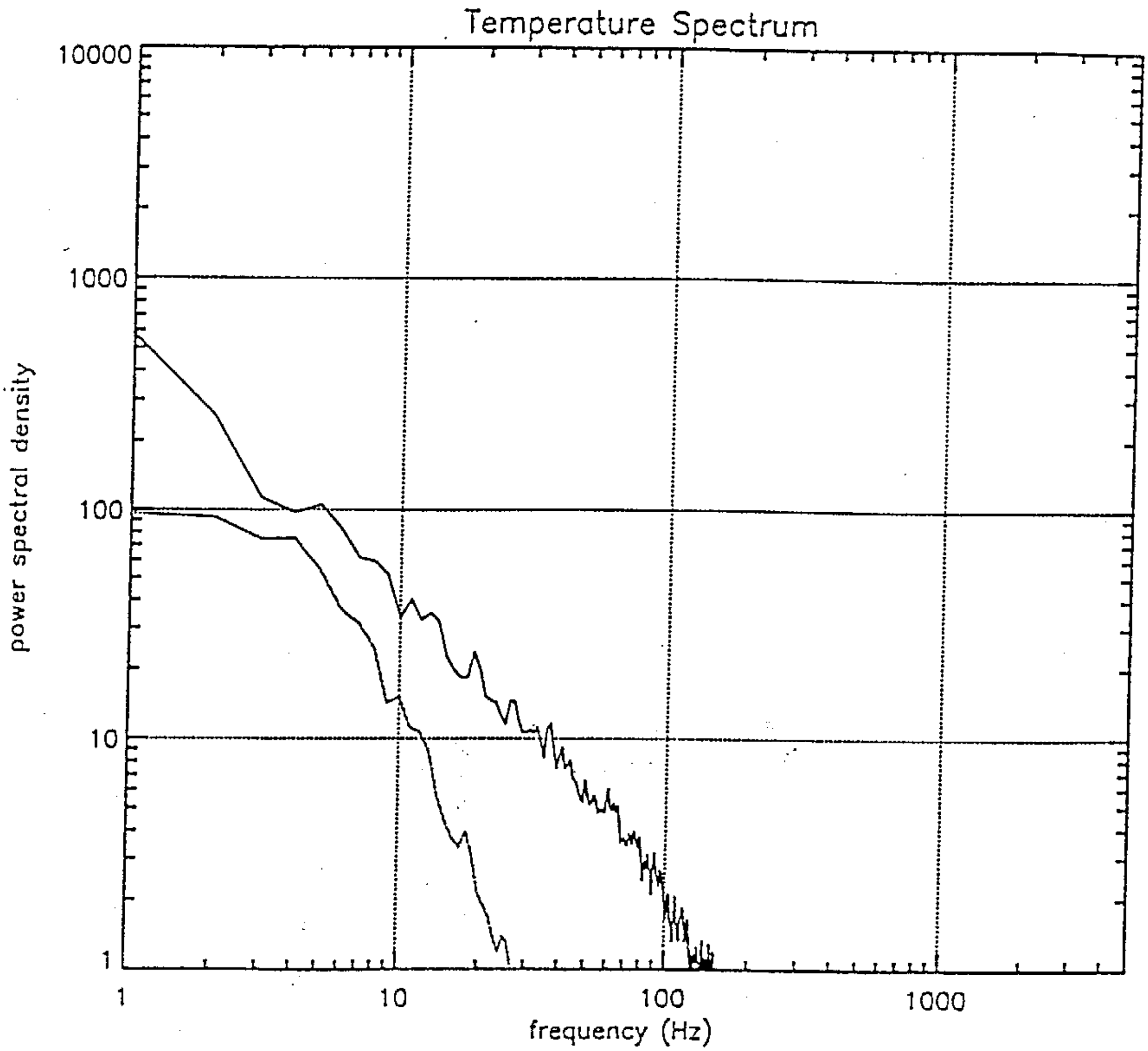
Fluctuating Temperature Contour

Case 12

S=0.7; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.00; x/D=0.59



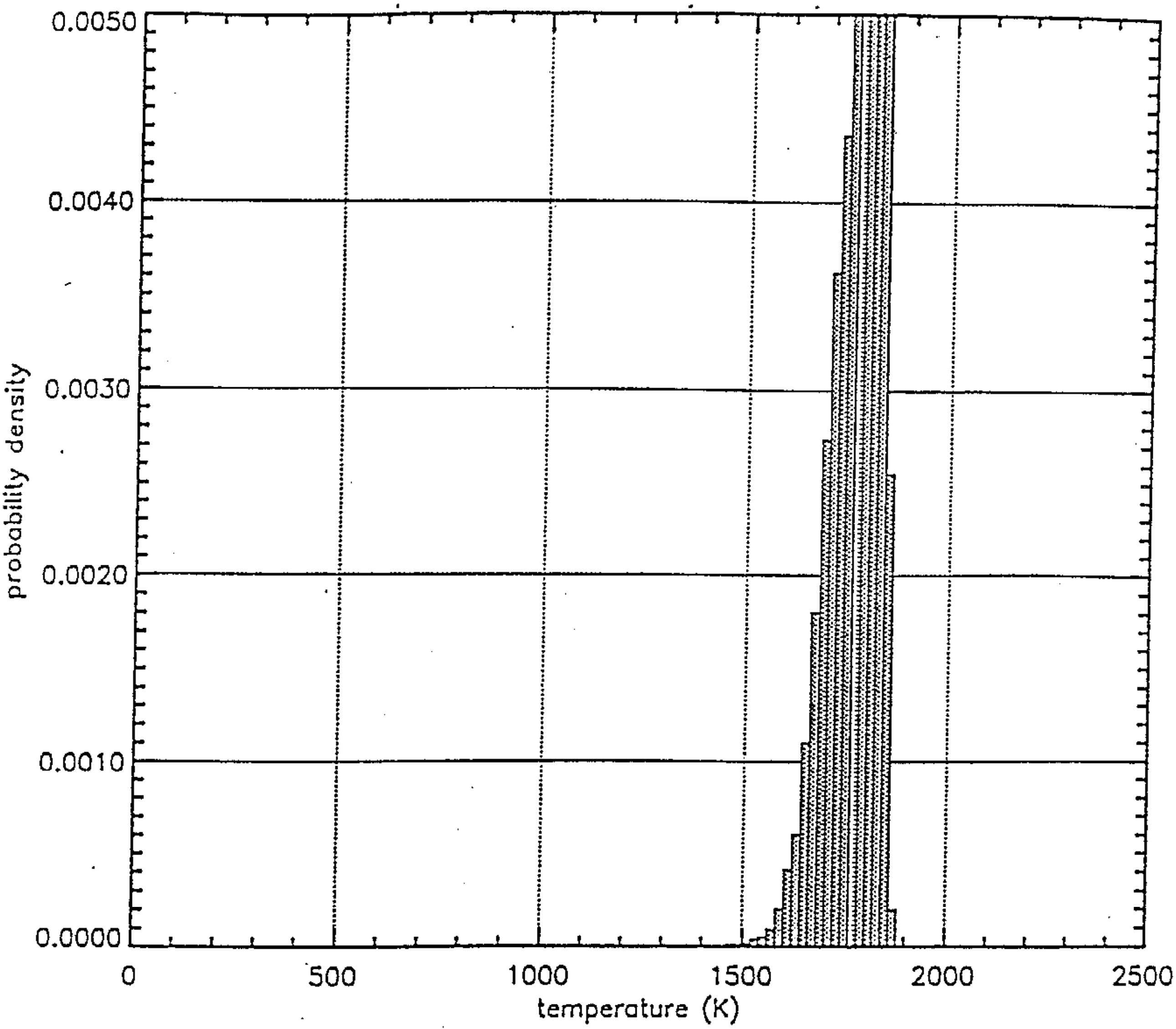
Power Spectral Density

Case 12

S=0.7; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.00; x/D=0.59



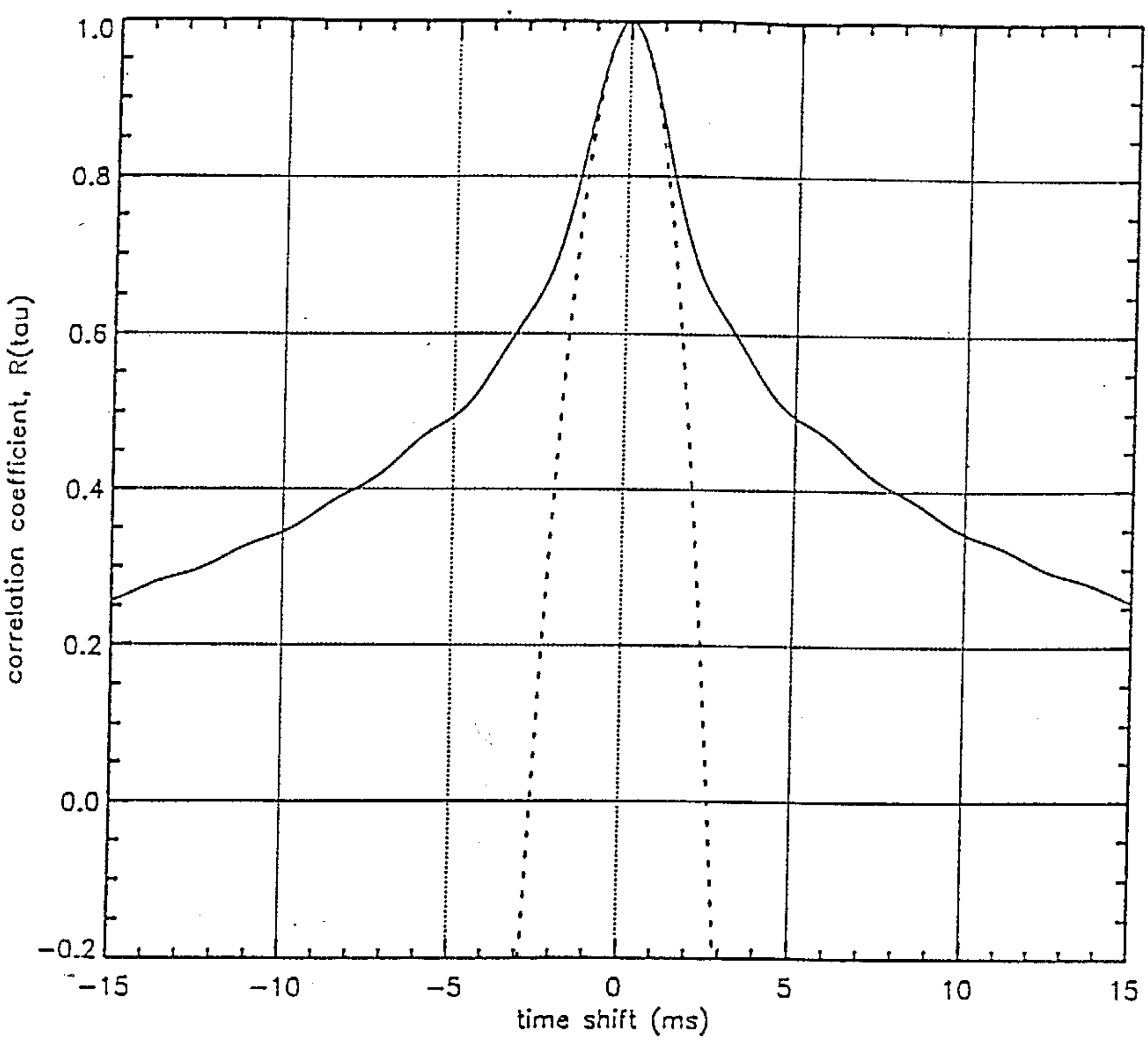
Probability Density

Case 12

S=0.7; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.00; x/D=0.59



Correlation coefficient

Integral scale=14.14 ms

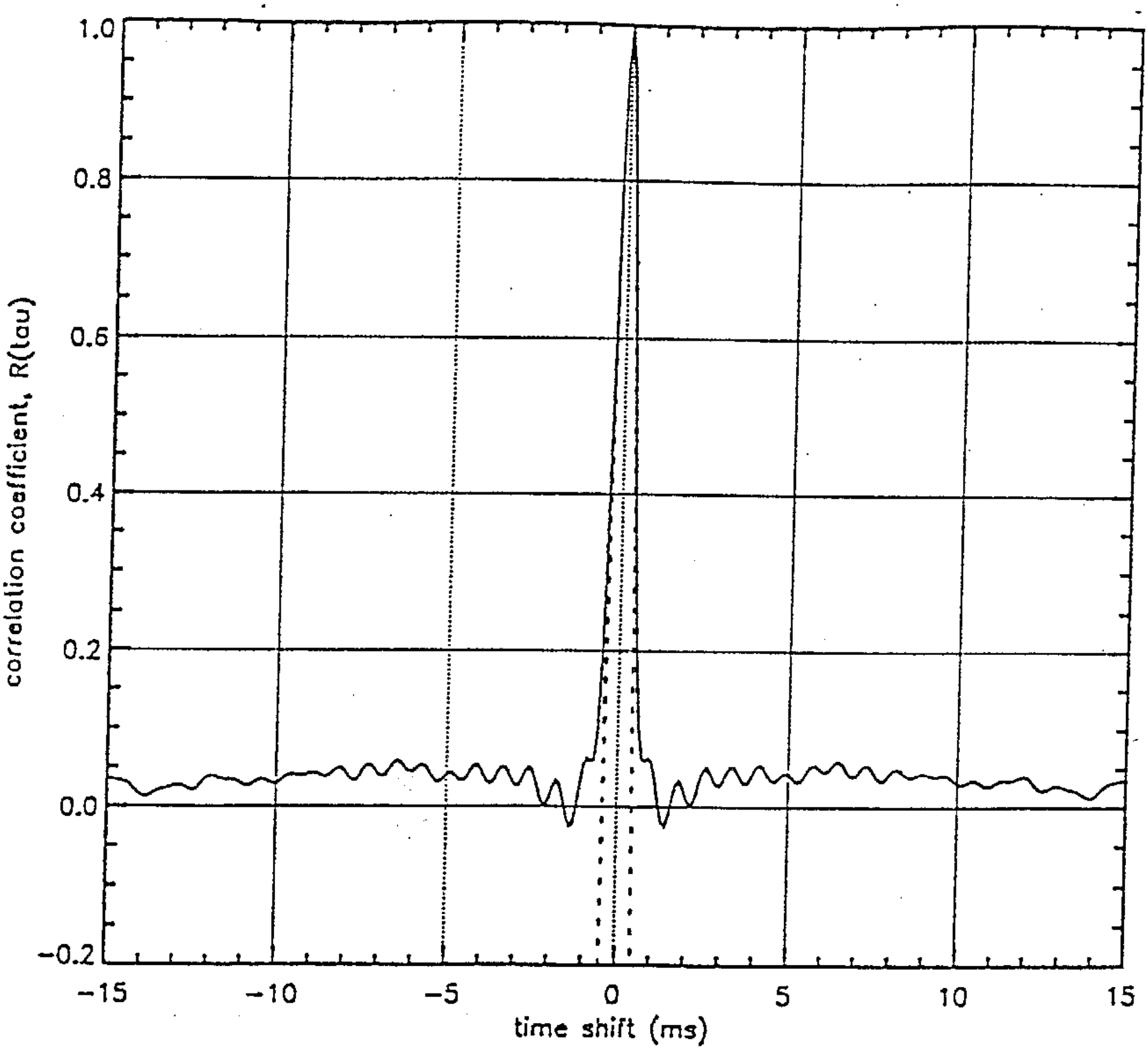
Micro-scale=2.62 ms

Case 12

S=0.7; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.59; x/D=0.59



Correlation coefficient

Integral scale=1.69 ms

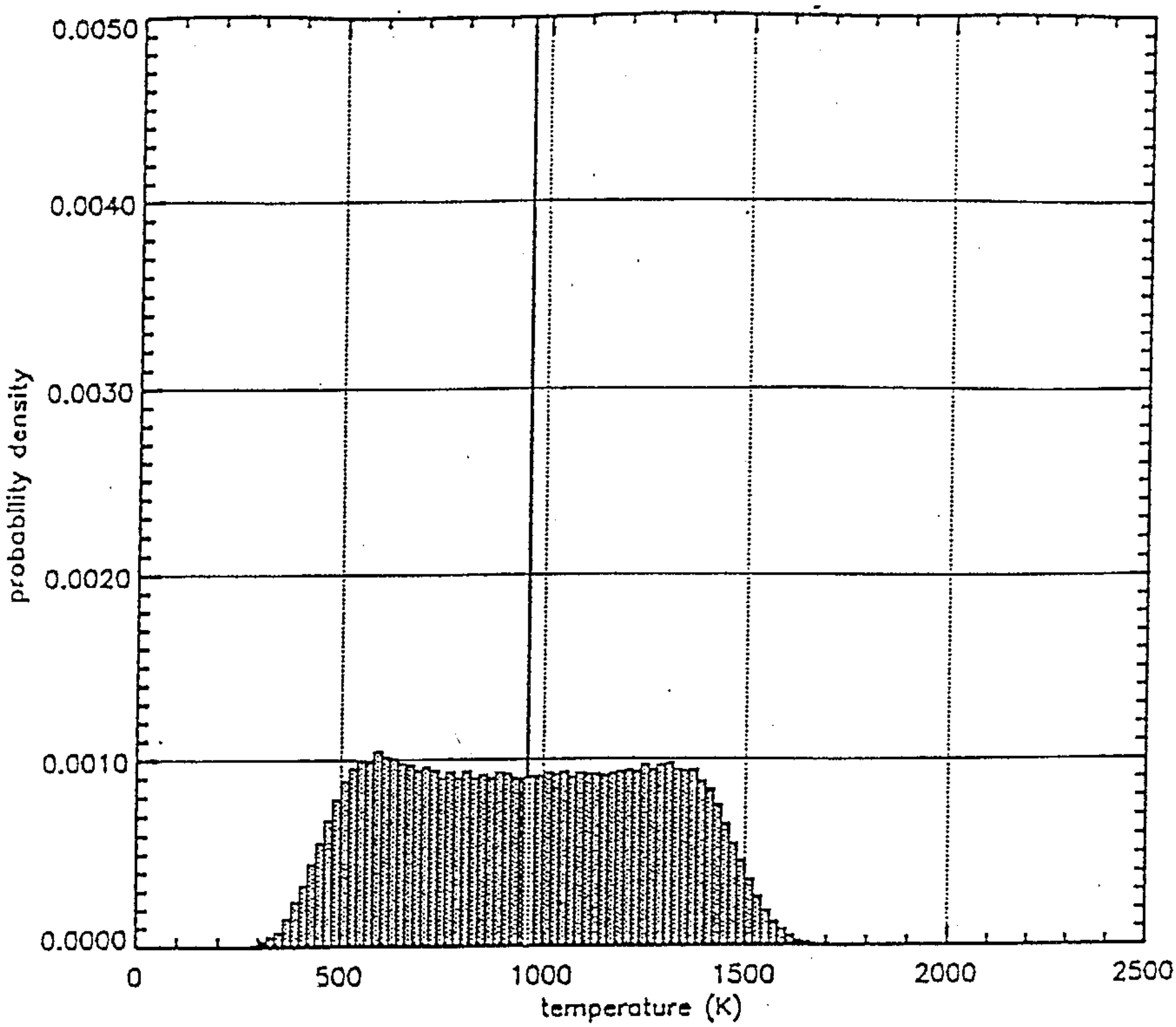
Micro-scale=0.43 ms

Case 12

S=0.7; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.59; x/D=0.59



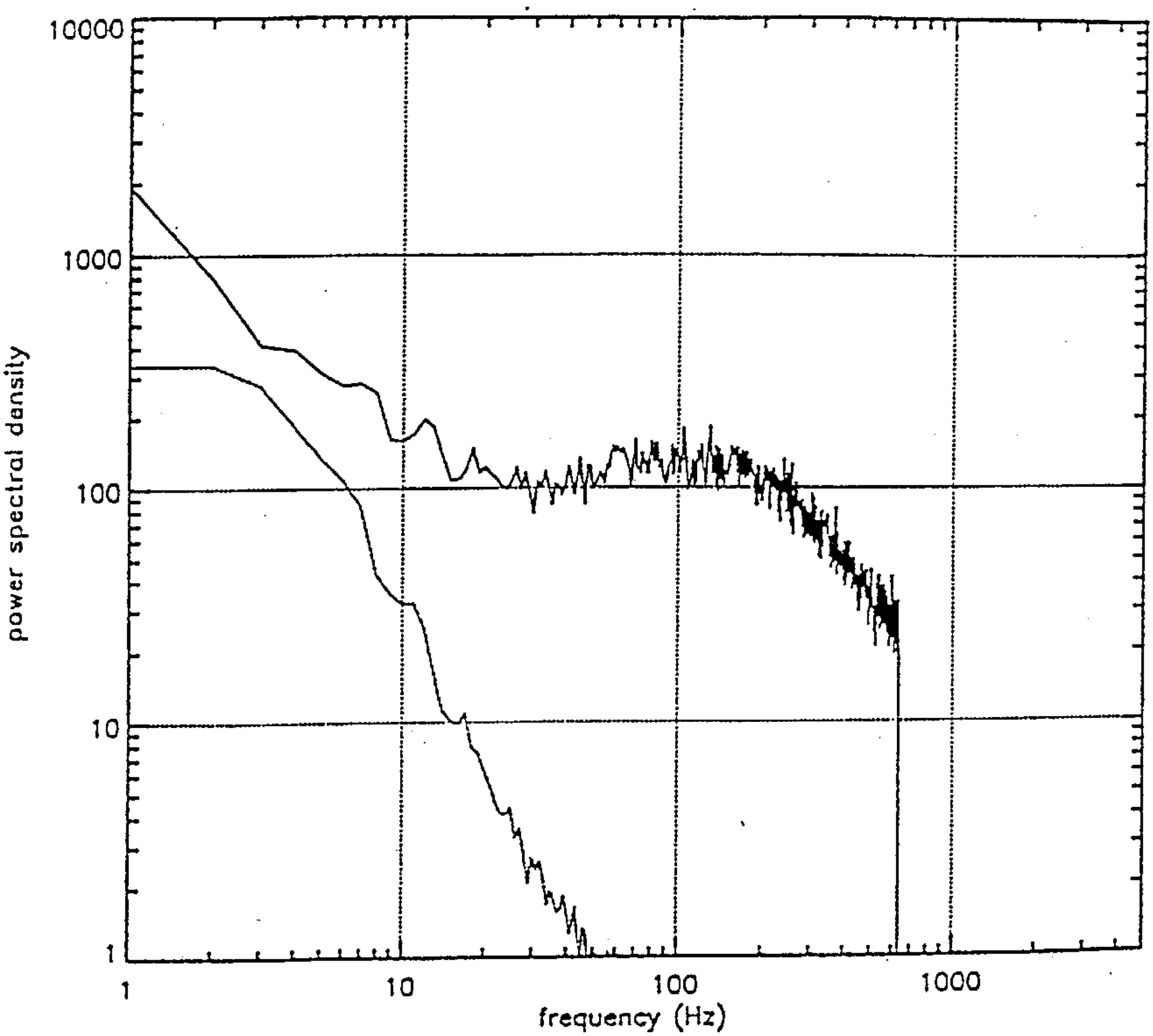
Probability Density

Case 12

S=0.7; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.59; x/D=0.59



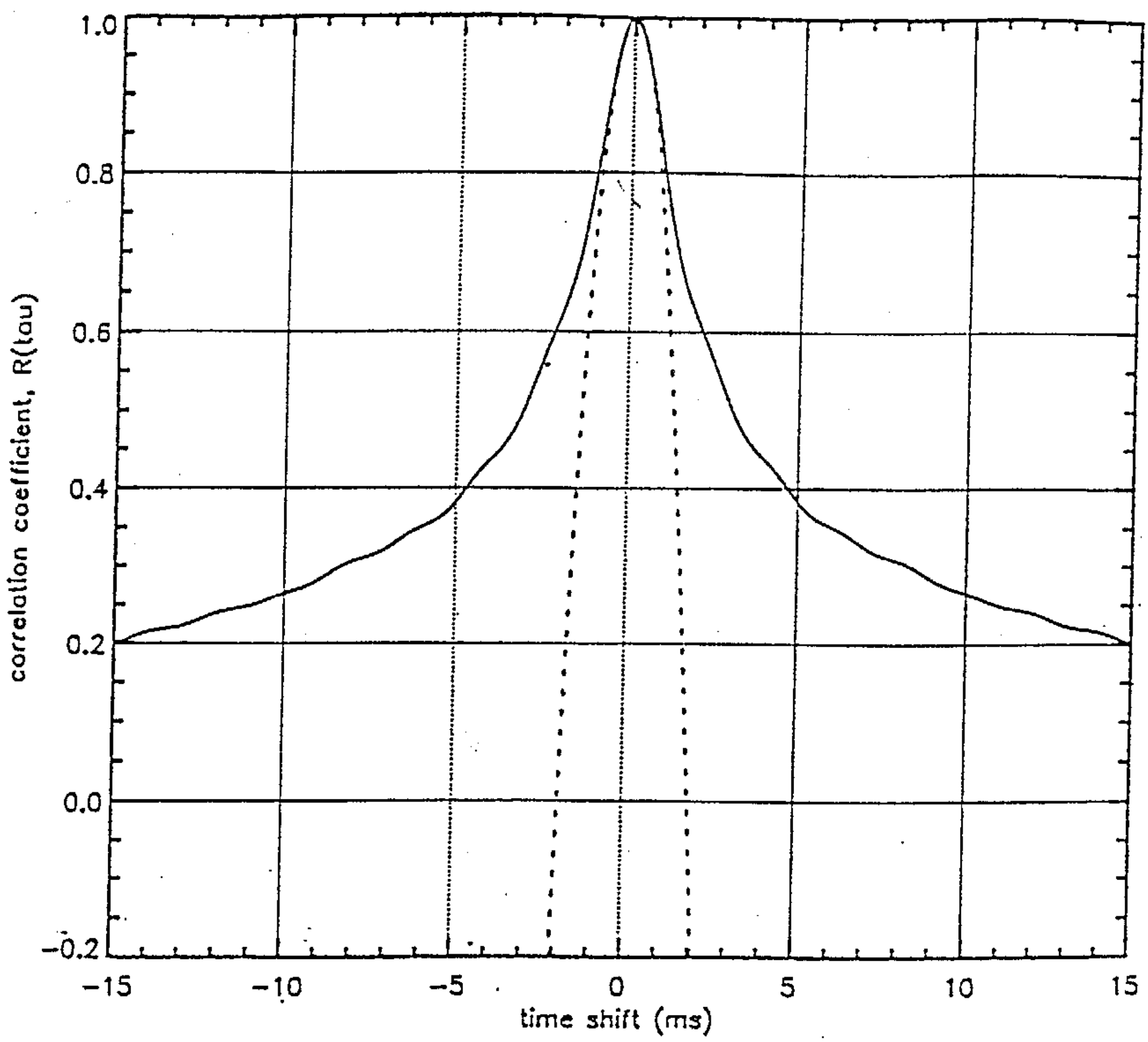
Power Spectral Density

Case 12

S=0.7; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.00; x/D=2.05



Correlation coefficient

Integral scale=11.60 ms

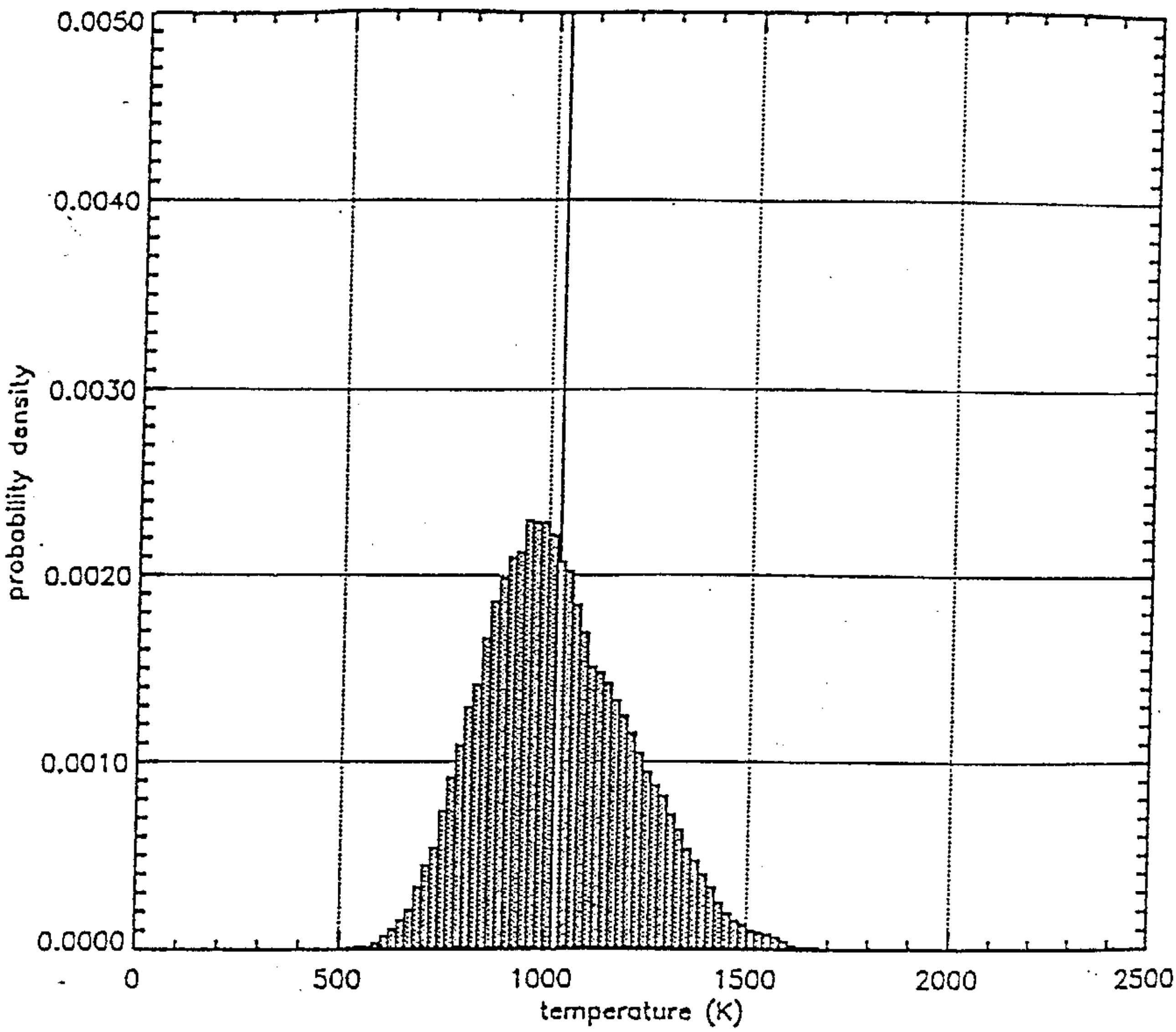
Micro-scale=1.91 ms

Case 12

S=0.7; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.00; x/D=2.05



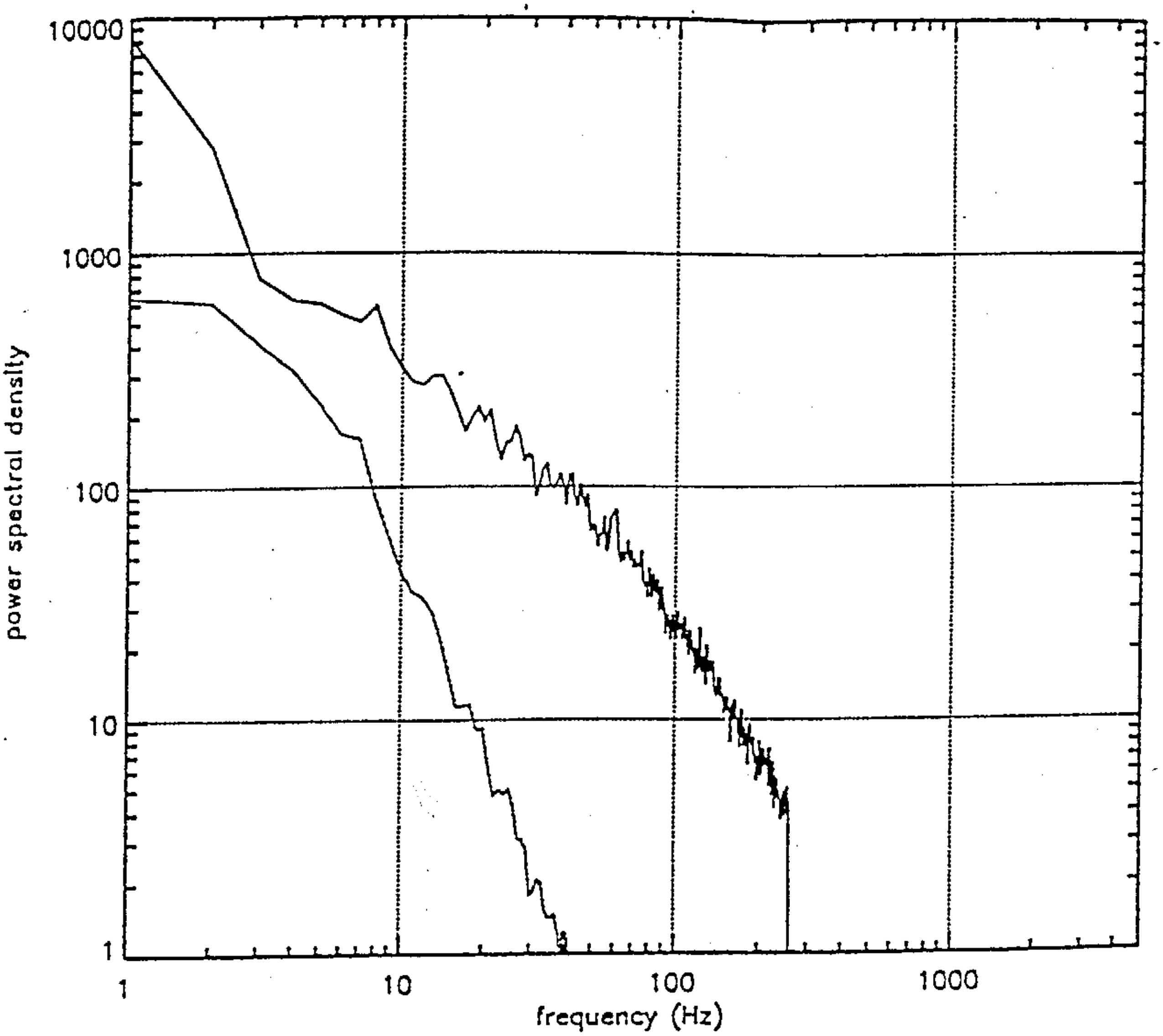
Probability Density

Case 12

S=0.7; M≈0.3; ϕ_{total}=0.462;

ϕ_{cp}=0.7; ϕ_{an1}=0.6; ϕ_{an2}=0.391

Location: r/D=0.00; x/D=2.05



Power Spectral Density

Flame Temperature, Emissions and the Corresponding Characteristic Time Scales at Different Regions of the Flames

	Flame 1	Flame 2	Flame 3	Flame 4	Flame 5	Flame 12
Burner Exit (at $r = 0, z = 0$)						
Mean Compensated Temperature	852.4 K	1761.1 K	1113.3 K	1736.9 K	1129.3 K	1900.6 K
Fluctuating Temperature	511.3 K	107.6 K	481.8 K	70.3 K	694.4 K	11.84 K
Thermal Microscale Time	0.59 ms	0.40 ms	0.41 ms	0.45 ms	0.39 ms	2.84 ms
Thermal Intergral Time	2.33 ms	2.33 ms	2.16 ms	4.32 ms	1.64 ms	9.06 ms
Central Recirculation Zone (at $r = 0, z = 0.29\ d$)						
Mean Compensated Temperature	1788.5 K	1784.5 K	1778.7 K	1746.4 K	1758.8 K	1850.9 K
Fluctuating Temperature	95.6 K	58.1 K	62.7 K	84.3 K	97.3 K	25.7 K
Thermal Microscale Time	0.52 ms	1.88 ms	0.75 ms	2.34 ms	0.67 ms	2.66 ms
Thermal Intergral Time	2.74 ms	7.52 ms	5.79 ms	14.39 ms	5.00 ms	12.82 ms
Shear Layer (at $r = 0.49\ d, z = 0.29\ d$)						
Mean Compensated Temperature	1153.1 K	1247.1 K	1193.2 K	1647.4 K	1148.7 K	932.8 K
Fluctuating Temperature	344.4 K	312.9 K	344.1 K	178.3 K	417.1 K	191.5 K
Thermal Microscale Time	0.28 ms	0.22 ms	0.24 ms	0.25 ms	0.23 ms	0.36 ms
Thermal Intergral Time	1.15 ms	1.22 ms	0.79 ms	2.80 ms	0.45 ms	1.86 ms
Post Flame Region (at $r = 0, z = 2.34\ d$)						
Mean Compensated Temperature	797.5 K	897.5 K	749.6 K	785.6 K	767.6 K	899.9 K
Fluctuating Temperature	127.1 K	147.6 K	98.4 K	100.8 K	94.9 K	137.9 K
Thermal Microscale Time	1.92 ms	1.35 ms	1.37 ms	1.08 ms	1.16 ms	2.18 ms
Thermal Intergral Time	11.8 ms	9.15 ms	12.5 ms	7.59 ms	9.83 ms	12.1 ms
Emission Data (at $r = 0, z = 2.34\ d$)						
NO_x	1.1 ppm	0.7 ppm	0.6 ppm	0.8 ppm	0.7 ppm	1.45 ppm
HC	0.66%	1.16%	1.29%	1.35%	1.34%	0.91 %
CO	1494 ppm	1784 ppm	1695 ppm	1696 ppm	1784 ppm	1222 ppm
CO2	2.48%	2.05%	1.75%	1.90%	1.85%	1.94 %

Summary

- Global flame features are effected by flow, burner geometry and operational parameters
- Flame thermal signatures and flow field characteristics change significantly with swirl, and distribution of equivalence ratio and flow momentum
- Significant variation of OH concentration in premixed flames
- Combustion emission levels are effected by operational parameters and swirl distribution

Major accomplishments

- Quantified thermal non-uniformities in premixed and partially premixed flames
- Correlated integral thermal time scales with overall emission levels
- Quantified effect of swirl, flow momentum and equivalence ratio distribution on the flame structure
- Detailed data can be used for design guidelines in advanced gas turbine combustors

Interaction With Industry

- Pratt & Whitney
- Allied Signal
- Allison